The graceful exit from the anomaly-induced inflation: supersymmetry as a key

I.L. Shapiro [1],

Departamento de Física – ICE, Universidade Federal de Juiz de Fora, MG, Brazil

Abstract. *The stable version of the anomaly-induced inflation does not require any fine tuning and provides sufficient expansion of the Universe. The non-stable version (Starobinsky model) provides the graceful exit to the FRW phase. We indicate the possibility of the inflation which is stable at the beginning and unstable at the end. The effect is due to the soft supersymmetry breaking and the decoupling of the massive sparticles at low energy. Alternative mechanism is based on the spectrum of neutrino masses.*

The inflation solves so many problems of the Early Universe that there are not so much doubts that it really took place (see, e.g. [1]). On the other hand, the conventional inflaton-based approach requires an exact fine-tuning of the form of the inflaton potential or initial data. Some people believe that there must be a natural mechanism for inflation, which should originate from the vacuum quantum effects of matter fields. The desired solution would not require any fine-tuning neither for initial conditions nor for the graceful exit to the Friedmann-Robertson-Walker (FRW) power-low expansion phase. The purpose of this letter is to suggest a qualitative version of such a mechanism. Our approach is based on the Starobinsky model [2, 3, 4, 5, 6, 7] and supersymmetry (SUSY). We shall also make use of the fact that SUSY is not seen in the low-energy phenomena.

Consider the vacuum quantum effects in the Early Universe. One may suppose that the typical energy of quantum processes is below the Planck scale. Then, the appropriate framework is not the string theory but some quantum field theory. Furthermore, at the energies greater than the masses of the particles one can apply an approximation in which the masses of the fields are negligible. The matter filling the Universe is characterized by pressure p and energy density ρ. The standard relation $\rho = 3p$ holds in the ultra-relativistic limit, consequently, the matter decouples from the conformal factor of the metric. This means local conformal (Weyl) invariance for the quantum fields [6]. Then the geometry of the space-time is influenced by the vacuum quantum effects of conformal matter fields. These effects can be taken into account through the conformal anomaly [2, 4, 3, 5, 6] and this may lead to inflation [3]. On the other hand, the masses of particles may become relevant at lower energies. Then, at the intermediate scale, the anomaly-induced action can

[1] On leave from Tomsk Pedagogical University, Russia. E-mail: shapiro@fisica.ufjf.br

serve as a model for the mass-independent part of the effective action [4, 3, 8]. The leading effect of particle masses would be the renormalization of the Einstein-Hilbert term in the vacuum action. In this paper we are using an approximation in which the quantum effects of masses of particles are not taken into account. The detailed investigation of their influence will be given elsewhere [9].

Suppose that the underlying matter theory has N_0 real scalars, $N_{1/2}$ Dirac spinors, and N_1 vectors. The vacuum quantum effects originate from the virtual particles (not from the real ones). Therefore, the numbers $N_0,\, N_{1/2},\, N_1$ correspond to the particle content of the theory. However, they do not describe the real matter which might fill the Universe. Another supposition is that the interaction between quantum fields is weakened at high energies due to the asymptotic freedom such that the one-loop contributions play the leading role. Thus, our model is a curved space-time with the geometry influenced by the one-loop vacuum quantum effects of the Weyl invariant free matter fields.

The classical action of vacuum can be very complicated and might have infinitely many local and non-local terms. However, in order to have a renormalizable theory, this action has to include, at least, three terms:

$$S_{vac} = \int d^4x\sqrt{-g}\, \Big\{ l_1 C^2 + l_2 E + l_3 \Box R \Big\}\,. \tag{1}$$

Here, $l_{1,2,3}$ are some parameters, C^2 is the square of the Weyl tensor and E is the integrand of the Gauss-Bonnet topological invariant. Action (1) consists of the conformal invariant and surface terms. Therefore, it does not influence the (homogeneous and isotropic) cosmological solution. Thus, if we add (1) to the Einstein-Hilbert action, then the usual FRW solution remains unaltered.

Let us postpone, for a while, the discussion about extra vacuum terms. The renormalization of action (1) leads to the conformal anomaly [10, 11, 12]

$$T = < T^\mu_\mu > = \,-\left(wC^2 + bE + c\Box R\right), \tag{2}$$

where $w,\, b,\, c$ are the β-functions for the parameters $l_1,\, l_2,\, l_3$ [2]

$$w = \frac{N_0 + 6N_{1/2} + 12N_1}{120\cdot(4\pi)^2}\,, \qquad b = -\,\frac{N_0 + 11N_{1/2} + 62N_1}{360\cdot(4\pi)^2}\,, \qquad c = \frac{N_0 + 6N_{1/2} - 18N_1}{180\cdot(4\pi)^2}\,. \tag{3}$$

One can construct the cosmological model by using the anomaly [3], however, it is instructive to use the effective action [13, 14, 15]. The quantum correction $\bar{\Gamma}$ to the classical action of vacuum is related to the anomaly

$$-\,\frac{2}{\sqrt{-g}}\, g_{\mu\nu}\, \frac{\delta \bar{\Gamma}}{\delta g_{\mu\nu}} = T\,. \tag{4}$$

[2]We notice that the contribution of the Weyl spinor is half of that for the Dirac spinor and the contribution of complex scalar is twice the one of the real scalar.

The solution of this equation [13, 14] can be found separately for different terms in (2). The following relations hold for the conformally transformed metric $g_{\mu\nu} = \bar{g}_{\mu\nu} \cdot e^{2\sigma}$:

$$R = e^{-2\sigma}\,[\bar{R} - 6(\bar{\nabla}\sigma)^2 - 6\Box\sigma]\,, \qquad \sqrt{-g}(E - \frac{2}{3}\Box R) = \sqrt{-\bar{g}}(\bar{E} - \frac{2}{3}\Box\bar{R} + 4\bar{\Delta}\sigma)\,,$$

where $\Delta = \Box^2 + 2\,R^{\mu\nu}\nabla_\mu\nabla_\nu - \frac{2}{3}\,R\Box + \frac{1}{3}\,(\nabla^\mu R)\nabla_\mu$ is a self-adjoint conformally covariant operator. For the remaining term one can use another relation

$$-\,\frac{2}{\sqrt{-g}}\,g_{\mu\nu}\,\frac{\delta}{\delta g_{\mu\nu}}\,\int d^4x\sqrt{-g}\,R^2 = 12\,\Box R\,. \tag{5}$$

Then, we arrive at the following general solution for the effective action [13, 14, 15]

$$\bar{\Gamma} = S_c[\bar{g}_{\mu\nu}] + \int d^4x\sqrt{-\bar{g}}\,\{w\sigma\bar{C}^2 + b\sigma(\bar{E} - \frac{2}{3}\Box\bar{R}) + 2b\sigma\bar{\Delta}\sigma\,\} - \frac{3c+2b}{36}\int d^4x\sqrt{-g}\,R^2\,, \tag{6}$$

where $S_c[g_{\mu\nu}]$ is some unknown conformal-invariant functional. The S_c-term is the only indefinite component of the solution (6). This term is relevant when we consider metric perturbations [7] but, in the case of conformally flat metric, solution (6) is the *exact* quantum correction to the classical action of vacuum. The second term on the *r.h.s.* of (6) is non-covariant but it can be rewritten in a covariant non-local form [13, 7] [3].

Now we are in a position to discuss the arbitrariness in the classical action of vacuum. It is very important that this is the action of an *external* gravitational field and that the metric is not quantized. As it was already mentioned above, one can add to the vacuum action (1) any local or non-local terms. In particular, one can introduce terms similar to those which emerge as quantum corrections (6). In this way, one can change the numerical coefficients of *all* terms in anomaly (2) or even cancel the anomaly completely. There is some peculiarity in the last statement. If one insists that the classical action of vacuum should be local, then only the last $\int\sqrt{-g}\Box R$-term in (2) can be modified by introducing the $\int\sqrt{-g}R^2$-term into the classical action. Sometimes, this operation is called "introducing finite counterterm".

As to the cosmological applications, the introduction of some ($\int\sqrt{-g}R^2$-type or non-local) extra terms into the classical action of gravity may be equivalent to the introduction of inflaton-like fields (see, e.g. [17, 7]). From our point of view, the necessity to adjust the classical action of vacuum *after* the calculation of quantum correction to it means that the program of "natural" inflation fails. Hence, we are not going to introduce any special vacuum terms. Neither the coefficient of the $\int\sqrt{-g}R^2$-term will not be fine-tuned. We assume that this coefficient is essentially smaller than the one generated by the anomaly and then, for the sake of simplicity, set it to zero.

The cosmological model is based on the action

$$S_{total} \;=\; -\,M_P^2\int d^4x\,\sqrt{-g}\,R \;+\; S_{conformal\,matter} \;+\; S_{vac} \;+\; \bar{\Gamma}\,, \tag{7}$$

[3] The non-local nature of the anomaly contribution has been first noticed in [16].

where $M_P^2 = 1/16\pi G$ is the square of the Planck mass and the quantum correction $\bar{\Gamma}$ is given by (6). It proves useful to introduce the following variables: conformal factor $a = e^\sigma$, physical time t (where $dt = a(\eta)d\eta$ and η is the conformal time) and $H(t) = \dot{\sigma}(t)$. For the conformally flat case $\bar{g}_{\mu\nu} = \eta_{\mu\nu}$, the equation for $H(t)$ has the form [6]

$$\dddot{H} + 7\ddot{H}H + 4\left(3 - \frac{b}{c}\right)\dot{H}H^2 + 4\dot{H}^2 - 4\frac{b}{c}H^4 - \frac{2M_P^2}{c}\left(2H^2 + \dot{H}\right) = 0\,, \tag{8}$$

The special inflationary solution corresponds to $H = const$:

$$H = \pm\frac{M_P}{\sqrt{-b}}\,, \qquad a(t) = a_0 \cdot \exp Ht\,, \tag{9}$$

where the positive sign signifies inflation [3]. We remark that two other similar solutions for the FRW metric with $k = \pm 1$ have been found in Ref. [3].

The next step is to study the stability of inflationary solution under fluctuations of the conformal factor $a(t)$. The analysis of stability can be performed analytically [3] or numerically [6]. Solution (9) is stable under fluctuations of the conformal factor $a(t)$ if the particle content of the underlying quantum theory satisfies the condition $\frac{b}{c} < 0$ [3]. By using eq. (3), we arrive at the following criterion of stability [7]:

$$N_1 < \frac{1}{3}N_{1/2} + \frac{1}{18}N_0\,. \tag{10}$$

If this constraint is satisfied, then the inflation starts independent on the initial conditions. The numerical analysis of [6] shows that the stabilization of inflation performs in a fraction of the Planck time and the Universe needs just 10 - 100 Planck times (depending on the particle content) to expand into necessary 65 e-folds. One can imagine that there was some string phase transition at the Planck scale. As all massive string modes decouple, we are left with the ultra-relativistic matter described by field theory. For the conformal massless fields, the leading quantum phenomena is the anomaly, and the inflation starts for any initial conditions. The problem is that the stable inflation is eternal and no simple receipt is known for the graceful exit to the FRW phase. The possible solutions of this problem were discussed in Refs. [6, 7] using the effective field theory approach. In particular, we have supposed that when the typical energy decreases, the masses of matter particles become relevant and the deviation of $a(t)$ from the exponential behaviour might lead to the graceful exit. To some extent, this letter is devoted to the realization of this idea (see also [9]).

Let us also mention Ref. [19]. In this paper the classical action of vacuum is chosen in such a way that the total $\int\sqrt{-g}R^2$-term is absent. Then, the inflation is stable but it can be (according to [19]) destabilized by metric fluctuations. Although, this kind of solution is theoretically possible, it does not obviously fit with the effective approach and we will not discuss it here.

The non-stable version of this inflationary model has been studied in [3, 8, 5, 18]. Indeed, the non-stable inflation has great advantage: it easily breaks and one can achieve the graceful exit to the FRW phase [5]. Furthermore, one meets rapid oscillations of the conformal factor after the breaking and this may produce the reheating [5]. We remark that the anomaly-induced effective action (7) includes the massive degree of freedom which has been called in [18] the second instanton. The decay of this mode into massive particles has been discussed in [8, 5, 18]. One can remark at this point that the massive mode of the conformal factor of the metric is not a fundamental field but instead it is a degree of freedom induced by the quantum effects of matter fields. If some matter field decouples (say, because it has a large mass), then it does not contribute to the massive mode of σ anymore and the coefficients $N_0,\, N_{1/2},\, N_1$ change correspondingly. On the other hand, since this induced mode interacts with matter and has its proper energy, the last can transfer into the real (not virtual) matter sector, especially through the creation of particles.

The shortcoming of the non-stable inflation is that without some "strong measures" it does not last long enough and the Universe does not expand sufficiently. The necessary "strong measures" have been discussed in [5]. They consist (in our interpretation) in the introduction of the $\int\sqrt{-g}R^2$ term into the classical action. Furthermore, in order to achieve a sufficient inflation, the total coefficient of the $\int\sqrt{-g}R^2$ term must be negative and be of the order 10^{-9}. Taking into account that the induced value of this coefficient is about 10^{-3}, one needs an extremely exact fine-tuning of the classical action. Namely, one has to choose the coefficient of the $\int\sqrt{-g}R^2$-term in the classical action in such a way that it cancels the induced counterpart in (6) and the overall sum becomes about million times smaller than each of the summands. As we have already mentioned, the introduction of the classical terms which cancel the quantum corrections can not give "natural" inflation.

Let us summarize. We have two sorts of the anomaly-induced inflation: stable and unstable. The advantage of the stable one is that it does not depend on the initial data. However, it remains unclear how the inflation stops. On the contrary, the non-stable inflation stops immediately and one is forced to perform a fine-tuning in order to achieve the necessary expansion of the Universe. Indeed, both versions do not look perfect if they are considered separately. It seems that the best situation would be to have the inflation which is stable at the beginning and unstable at the end. If one could switch from one to another in a natural way, this could be the desired explanation of inflation.

Now we come back to the condition of stability (10), which depends on the particle content. At present, the observed spectrum of particles fits with the Minimal Standard Model (SM). Since there is some controversy in the literature [19], we shall present a few details. The SM includes 6 quarks, each of them has 2 chiralities and 3 colors. Hence, quarks contribute $N_{quarks} = 18$. Furthermore, there are 6 leptons. Since all the neutrino are supposed to be massive nowadays, each lepton has two chiralities and we have $N_{leptons} = 6$. Indeed, there may be one more (so called sterile) neutrino, but it is not present in the SM, and will not be included here. The scalar sector has one Higgs doublet $N_0 = 4$, while the vector one has 8 gluons, $W^{\pm}$, Z and photon. After all, we have, for the SM, $N_0 = 4,\, N_{1/2} = 24,\, N_1 = 12$. Then, Eq. (10) indicates to the non-stable inflation and this perfectly fits with our dream to have unstable inflation at the end. We mention that even adding one more sterile neutrino does not change this conclusion.

Let us remember that the anomaly-induced inflation is supposed to occur at the sub-Planck energy domain. There are many reasons to expect that the particle spectrum at this scale goes beyond the SM. In particular, it may happen that the high-energy theory possesses supersymmetry. Let us, for example, look at the particle content of the Minimal Supersymmetric Standard Model (MSSM). This model has $N_1 = 12$ as in the SM. Furthermore, all fermions of the SM are present in the MSSM. Now, since quarks and leptons can not be superpartners of the vector constituents, one needs to introduce additional superpartners (gaugino) to all the vectors. The same concerns Higgs particles, to which one adds superpartners higgsino. Thus, we have $N_{1/2} = 32$ for the MSSM. Finally, the scalar sector includes two Higgs doublets and numerous superpartners of the fermions: squarks and sleptons. The total amount of scalars is $N_0 = 104$. It is easy to see that this particle content provides stability in (10). In fact, similar result can be expected for any realistic supersymmetric model. The supersymmetric extension of the gauge theory implies the replacement of any vector multiplet by the $N = 1$ vector superfield. Moreover, one has to add superpartners to the fermions in such a way that they form chiral superfields. Both operations increase the number of spinors and scalars in (10) and we obtain the stable inflation.

One can see that in this framework the situation when the anomaly-induced inflation is stable at the beginning and unstable at the end means exactly that supersymmetry breaks at the last stage of inflation. Next, since the typical energy scale decreases during the inflation, this can be associated with the supersymmetry breaking at low energies. Let us explain the last statement in more detail. The Feynman diagrams which contribute to the anomaly-induced action (6) consist of a quantum bubble of matter (non-gravitational) fields with external tails of the σ field (see the Figure). According to the Appelquist and Carazzone theorem [20], the loop of massive field decouples when the energy of external lines becomes much smaller than the mass of the quantum field in the loop. One has to notice that if the origin of masses of quantum fields is not the Spontaneous Symmetry Breaking, the Appelquist and Carazzone theorem applies nicely. The massive sparticles decouple when the typical energy of the external lines of the field σ becomes smaller than the masses of these particles. Thus, our scheme of inflation is realized in the most natural way for the soft SUSY breaking. At present, this looks phenomenologically as the most acceptable way of breaking SUSY (see, e.g. [21]).

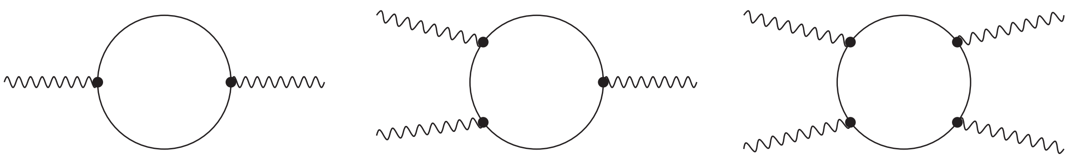

Figure. The samples of the one-loop Feynman diagrams which contribute to the anomaly. The bubble of the matter field has 2,3 or 4 external lines of the field σ.

The important problem is the duration of inflation. Since the breaking of the exponential inflation occurs in a very short time [5], this is equivalent to two questions:

i) What is the SUSY breaking scale?

ii) How to evaluate the energy of the σ-field quanta in external lines of diagrams?

The first problem has been widely discussed in the literature (see, e.g. [21]). The most popular is the situation when the supersymmetry breaks softly at some typical energy above the electroweak scale $M_F \approx 300\,GeV$. At the same time, one cannot exclude alternative options like the SUSY breaking at the GUT scale. Another possibility is the existence of some very light sparticles with feeble interaction to the observable sector. For instance, some models of neutrino oscillations include sterile neutrino, which could be a remnant of the GUT SUSY. The answer to the *ii)* question is also not simple. Solution (9) depends on a single dimensional parameter M_P and it is not obvious how the energy of the σ-quanta changes with time.

Consider also some particular possibility which is not directly based on SUSY. The renormalization group approach in curved space-time [22, 12] links the variation of the energy scale with the rescaling of the metric. Then, the typical energy of the σ-quanta varies as $\mu_\sigma \sim 1/a(t)$. If we want to achieve the standard 65 e-folds, the scale has to change during the inflation by $65/\ln 10 \approx 28$ orders of magnitude. If the inflation starts at $M_P = 10^{19}\,GeV$, then it has to stop at the scale $\mu_{fin} \approx 10^{-9}\,GeV = 1\,eV$. Indeed, this corresponds to the supposed mass of the “heavy” couple of neutrino[4]. Since only the photon represents an active vector component at this scale, two light neutrinos correspond to the non-stable inflation (10). In this version of decoupling mechanism the inflation ends when the ”heavy” neutrinos decouple. In this form the scenario does not look perfect, in particular, because it supposes that the inflation holds during the nucleosynthesis epoch.

[4]We notice that the presence of the ”light” neutrino couple $N_{1/2} = 2$ does not stabilize the inflationary solution. Therefore, the above scheme can be successfully realized in any of phenomenologically acceptable versions of neutrino oscillations.

Another consequence is that the GUT scale must be identified with the Planck scale, otherwise, the inflation does not solve the monopole problem.

Now, one can construct a merger of two mechanisms. The renormalization group tells us that the total number of e-folds, from Planck scale to the neutrino decoupling scale $\approx 1\,eV$ is about 65. However, the renormalization group does not tell how the process was. One can imagine that the inflation started due to the SUSY particle content after the string phase transition. Then it lasted until the SUSY breaking at some scale above $M_F \approx 300\,GeV$. After that there is no SUSY and the unstable inflation breaks. Since it breaks very fast, one can not see any traces of the exponential inflation, and the expansion goes acording to the FRW rule (as it goes now [5]). In this period the nucleosynthesis occurs safely at the energy of order $0.1 - 1\,MeV$. So, the inflation takes "interval", but then it starts again when heavy spinors, gluons, W, $Z^{\pm}$ and Higgs decouple, so that one meets only photon and light leptons and quarks. Finally, the inflation ends when almost all massive particles (including the "heavy" neutrino), decouple. Taking the high energy scale of the "interval of inflation" into account, one can see that this interval and the first phase of inflation were relatively short in time, while the second phase was longer.

Alternatively, there is an attractive possibility that the renormalization group for the σ-quanta is more complicated, for it could exhibit the nontrivial IR fixed point [23, 24]. In this case the classical scaling relation $\mu_\sigma \sim 1/a(t)$ is violated and the final end of inflation occurs at higher energy scale. In order to complete the story, we notice that during the inflation the real matter and radiation in the Universe are in a non-equilibrium state, so that their typical energy changes very slowly. One can guess, that this could influences, also, the vacuum effects. The complete study must definitely include the investigation of non-equilibrium behaviour of matter and the physical effects like the creation of particles during the inflation.

In conclusion, we considered an attractive possibility of the anomaly-induced inflation which is stable at the beginning and unstable at the end. The transition may be caused by the decoupling of the massive particles. The most attractive example of this decoupling is given by the SUSY breaking but there can be other mechanisms. The detailed study of the decoupling is an interesting problem, and its solution may lead us to the natural mechanism for inflation. The final answer on whether the inflation was realy caused by the vacuum quantum effects, is due to experiments and observations. Nowadays, cosmology becomes an exact science, mostly because of the possibility to measure temperature fluctuations $\Delta T/T$ due to the density and metric perturbations. The analyzis of the gravitational waves on the background of the anomaly-induced inflation has been performed in [7] (see also [8] for the earlier work in this direction). The result for the perturbation spectrum is close to the one for the conventional inflaton model, and is in agreement with the

[5] We notice that the existing cosmological constant was not relevant at high energy scale.

existing Cobe data. The next important step is a similar analysis of the density perturbations, which can provide the material for the phenomenological analysis using available and anticipated observational data.

Acknowledgments. I am very grateful to A. Belyaev and J. Sola for useful explanations concerning SM and supersymmetry, and to Ed. Gorbar for critical reading the manuscript. The grant from CNPq (Brazil) is gratefully acknowledged.

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